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GENERALIZED SELECTION CHARTS FOR HARRISON AND TUBULAR INTERCOOLERS

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SUMMARY

A generalized selection chart for tubular cross-flow intercoolers and a similar chart for Harrison cross-flow intercoolers are presented. These charts make it possible to select intercoolers for any set of design conditions and under any limitations on dimensions and pressure drops. They are also useful for showing what changes in the characteristics of a given intercooler will improve its performance. A number of practical examples are given illustrating the use of the charts. In these examples the charts are applied to the selection of Airesearch tubular intercoolers and Harrison copper intercoolers.

INTRODUCTION

The fixed quantities in intercooler selection for which the values are known constitute the "design conditions." These design conditions include such quantities as the mass flow of engine air, the inlet and outlet temperatures of the engine air, the inlet temperature of the cooling air, the altitude for which the intercooler must be chosen, the airplane speed, and so forth. The unknown variables for which proper values must be chosen are the pressure drops for the engine air and for the cooling air, the three linear dimensions of the intercooler, the power consumption of the intercooler, and the mass flow of cooling air.

A method of selecting intercoolers is needed that properly takes into account all of the unknown variables and shows the effects of changing any one of the intercooler characteristics. The method must also be relatively easy to use. The problem of developing such a method is complicated by the number of unknown variables involved.

This problem has been attacked in a number of papers, the aims of which were, in general, to set up a simplified procedure to be followed in selecting intercoolers and to clarify the operation of intercoolers. Some degree of success in solving the problem has been attained; for example, references 1, 2, and 3 present plots of power consumption as a function of some of the other intercooler variables. These plots not only show some of the effects of changing these variables but also reduce the amount of calculation involved in the selection of intercoolers. Reference 4 shows how to construct selection charts for Harrison intercoolers of which the power consumption is a minimum for a fixed mass flow of cooling air. The results of this paper are valuable in that they make it possible to calculate the lower limit of power consumption attainable for a given set of design conditions. In reference 5 generalized equations are derived that describe the performance of heat exchangers installed in aircraft.

The purpose of the present paper is to submit intercooler selection charts based upon the equations developed in reference 5 and to illustrate their use. These charts are completely general, as the variables have been put into nondimensional, generalized form. The same chart can therefore be used for any set of design conditions. The charts take into account all the intercooler variables. The effects of changing any of these variables can be obtained from the charts. The charts presented make it comparatively easy to select, for a given set of design conditions, the intercooler that is most desirable with respect to dimensions, pressure drops, and power consumption.

The two types of intercooler for which charts are presented are the Harrison type and the tubular type. Each chart is applicable to any intercooler of similar general construction. Most of the constants that appear in the definitions of the generalized variables are functions of the internal dimensions of the intercooler, however, and these dimensions must be known before the chart can be used. In the present report one chart is applied to the Harrison finned copper intercooler, the internal geometry and dimensions of which are given in figure 1. The chart for tubular intercoolers is applied to the Airesearch aluminum tubular intercooler, for which the tube arrangement and dimensions are shown in figure 2. Large blueprints of the generalized selection charts (figs. 3 and 4) are available, on request, from the National Advisory Committee for Aeronautics.

In supplements to this report, the charts will be used in connection with intercoolers of other internal dimensions. These supplements will be published when sufficient data on dimensions and performance become available.

SYMBOLS

A frontal area of intercooler, square feet

c_1, c_2, c_3, c_4 empirical numerical constants

c_p specific heat of air at constant pressure, British thermal units per pound per degree Fahrenheit

C_D/C_L ratio of drag coefficient to lift coefficient of airplane, dimensionless

D tube diameter for tubular intercooler, feet

D_h hydraulic diameter of passage in Harrison intercooler, feet

f ratio of open to total frontal area, dimensionless

g acceleration due to gravity, 32.2 feet per second per second

h coefficient of heat transfer, British thermal unit per second per square foot per degree Fahrenheit

k thermal conductivity of air, British thermal unit per second per square foot per degree Fahrenheit per foot

K_1, K_2, K_3, K_4 constants

L length of air passage, feet

L_n length of intercooler in no-flow direction, feet

m_n center-to-center tube spacing normal to direction of air flow, feet

m_p center-to-center tube spacing parallel to direction of air flow, feet

M weight rate of flow, pounds per second

n number of tubes per square foot of intercooler face with ends of tubes

p static pressure, inches of mercury

Δp pressure drop, pounds per square foot

P power, horsepower

s effective cooling surface per unit length of tube, square feet per foot

T temperature of air, degrees Fahrenheit

v volume of intercooler, cubic feet

V speed of air, feet per second

V_0 speed of airplane, feet per second

u, v, x, y exponents

ϵ factor to account for weight of intercooler mounting, dimensionless

ζ mean temperature difference between engine air and cooling air divided by initial temperature difference, dimensionless

η duct efficiency, dimensionless

μ coefficient of viscosity of air, slugs per foot-second

ξ drop in temperature of engine air divided by initial temperature difference, dimensionless

ρ mass density of air, slugs per cubic foot

ρ_W weight density of intercooler, pounds per cubic foot

$\alpha_1 \ldots \alpha_8$, $\beta_1 \ldots \beta_4$ constants

Subscripts:

a flow across tubes

b flow through tubes

c cooling air

e engine air

t total

W weight

out outlet

A bar over a value indicates a mean value.

Constants:

$$K_1 = \frac{n\alpha_6}{\alpha_2\alpha_5 M_e c_p \xi}$$

$$K_2 = \left(\frac{\alpha_3\alpha_6}{\alpha_2}\right)^{1/v}$$

$$K_3 = K_2^{\,3-y}$$

$$K_4 = \frac{(\alpha_6)^{1/u}}{\alpha_5}$$

$$\alpha_1 = \frac{2c_1\mu_c^{\,x}}{g^{3-x}\rho_c^{\,2}\eta_c m_p D_c^{\,x} f_c^{\,2-x}} \quad \text{(for tubular-type intercooler)}$$

$$\alpha_1 = \frac{2c_1\mu_c^{\,x}}{g^{3-x}\rho_c^{\,2}\eta_c D_h^{\,1+x} f_c^{\,2-x}} \quad \text{(for Harrison type intercooler)}$$

$$\alpha_2 = \frac{\left(f_c\mu_c g\right)^u D_c^{\,1-u}}{k_c c_3 s_c}$$

$$\alpha_3 = \frac{\left(f_e\mu_e g\right)^v D_e^{\,1-v}}{k_e c_4 s_e}$$

$$\alpha_4 = \frac{2c_2\mu_e^{\,y}}{D_e^{\,1+y}\rho_e(f_e g)^{2-y}}$$

$$\alpha_5 = \epsilon \frac{C_D}{C_L} V_o \rho_W$$

$$\alpha_6 = \left(\frac{\alpha_5}{\alpha_1}\right)^{\frac{u}{3-x}}$$

$$\beta_1 = (3.71 \times 10^{-6}) \frac{\mu_c^{0.16}}{\rho_c^{2}} \text{ (for tubular-type intercooler)}$$

$$\beta_1 = (1.94 \times 10^{-5}) \frac{\mu_c^{0.16}}{\rho_c^{2}} \text{ (for Harrison type intercooler)}$$

$$\beta_2 = \frac{1}{10\mu_c^{0.2}}$$

$$\beta_3 = \frac{1}{10\mu_e^{0.2}}$$

$$\beta_4 = \frac{\mu_e^{y}}{10\rho_e}$$

Generalized variables:

$$\Delta p_e' = \frac{\alpha_5 K_1 M_e}{\alpha_4 K_3} \zeta \Delta p_e$$

$$\Delta p_c' = \frac{K_1 (\overline{T}_c + 460) M_e}{1.32 \eta_c \overline{p}_c} \frac{M_c}{M_e} \zeta \Delta p_c$$

$$L_e' = \frac{\alpha_5 K_1 M_e}{K_2} \zeta L_e$$

$$L_c' = \frac{K_1 M_e}{K_4} \frac{M_c}{M_e} \zeta L_c$$

$$L_n' = \frac{K_2 K_4}{K_1 M_e^{2}} \frac{L_n}{\frac{M_c}{M_e} \zeta}$$

$$v' = K_1 \alpha_5 \zeta v = K_1 \alpha_5 \zeta L_e L_c L_n = L_e' L_c' L_n'$$

$$P' = 550 K_1 \zeta (P_W + P_c)$$

DISCUSSION OF CHARTS

The selection charts (figs. 3 and 4) show the effects of separately changing each of the intercooler variables. The more important of these effects and the use of the charts in selecting the most satisfactory values for the variables are discussed in the following paragraphs.

Power expenditure.- A discussion of how the power expenditure varies is simplified by consideration of the curves of constant $\Delta p_e'$. The shape of these curves is such that they pass through a minimum P'. For a given value of $\Delta p_e'$, therefore, the point on the chart that represents the intercooler of smallest power consumption is easily found. The value of the abscissa $\Delta p_c'$, furthermore, is essentially the same for the minimum points of all of the $\Delta p_e'$ curves for a given type of intercooler. For tubular intercoolers this value is 0.4 and for Harrison intercoolers 0.6.

Too much importance should not be attached to selecting intercoolers of lowest power consumption. Power consumption is not the only factor to be considered. The $\Delta p_e'$ curves have small slopes to the right of the minimums. An intercooler that is represented by a point lying on the same $\Delta p_e'$ curve and some distance to the right of minimum P', therefore, does not use a great deal more power than the intercooler of minimum P'. Its dimensions and volume will, in general, be more satisfactory than those of the intercooler of minimum P'.

Volume and pressure drops.- The charts show how the pressure drops should be chosen in order that the volume of the intercooler be as small as is practicable. For a given $\Delta p_c'$, the larger the engine-air pressure drop, the smaller the volume. Likewise, for a given $\Delta p_e'$, the larger $\Delta p_c'$, the smaller the volume. As $\Delta p_c'$ is increased, however, the curves of constant $\Delta p_e'$ and constant v' become nearly parallel. Consequently, there is little advantage in choosing a value for $\Delta p_c'$ that is larger than the value it has when these curves become closely parallel. These effects are illustrated in examples II and III.

Cooling-air mass flow.- All the generalized intercooler variables are functions of the temperature difference t.

In particular, for given values of P' and v', the corresponding unprimed variables are proportional to $1/\zeta$. The power consumption and the volume, therefore, will be lowest for the smallest values of $1/\zeta$. Figure 5 is a plot of $1/\zeta$ as a function of the dimensionless ratio M_c/M_e with ξ as a parameter. Each curve of constant ξ contains a "knee." It is clear that to the right of the knee the value of $1/\zeta$ is essentially constant but to the left of the knee $1/\zeta$ varies rapidly and is also much larger. The power expenditure and the volume, therefore, will be much lower when M_c/M_e lies to the right of the knee, where $1/\zeta$ is small, than otherwise. The physical reason for this fact is that, if $1/\zeta$ is small, the temperature difference is large and the cooling surface and the volume which the intercooler must have are relatively small. The power to carry the intercooler is therefore also relatively small.

An upper limit to M_c/M_e is set by any limit that may be imposed on the value of L_n. For a given L_n', L_n is proportional to $\dfrac{M_c/M_e}{1/\zeta}$. Choice of too large a value for M_c/M_e results in an excessive value for L_n.

Inasmuch as $1/\zeta$ is nearly constant in the region to the right of the knee, a close approximation to its value for use in calculations is at once obtainable from figure 5, the assumption being made that the value of M_c/M_e is greater than its value at the knee. The method of finding the exact values of M_c/M_e and $1/\zeta$ will be pointed out in the solution of the illustrative examples.

<u>Fixed dimensions</u>.- The charts can be used for determining what mass flow of cooling air is necessary and what the pressure drops will be for an intercooler of given dimensions in order that it be capable of a given rate of heat dissipation. (See example IV in the following section.)

EXAMPLES

Illustrations of the use of the selection charts are given in the following five examples. In examples I to IV Airesearch intercoolers are selected and in example V a Harrison intercooler is selected. Some of the effects of changing the intercooler variables are discussed along with the examples.

According to the procedure used in the subject report, the selection of an intercooler is made in three major steps by the use of the selection forms at the end of the paper and the generalized selection charts (figs. 3 and 4). The first step is setting down the design conditions, which is accomplished by filling in form 1. The second step involves the computation of the values of the constants in the equations that define the generalized variables. These constants are functions of the type of intercooler, of the internal dimensions of the intercooler, and of the physical properties of the fluids. Figures 6, 7, and 8 are used for filling in forms 2 and 3 for Airesearch intercoolers and forms 4 and 3 (in that order) for Harrison copper intercoolers. The third step, which involves the use of the generalized charts (figs. 3 and 4), is discussed in the preceding section and in the examples that follow. In filling in form 1, a typical set of design conditions has been used.

Example I.- The problem is to select an Airesearch intercooler. The first step is to fill in form 1 with the design conditions. The second step is to fill in forms 2 and 3 by using figures 6, 7, and 8 and the data of form 1. The third step is accomplished as follows: Assume that the limits allowed on the pressure drops and on L_n are as given in the first column under Example I in table I. Because the dimensions of the intercooler are not known, the velocity of the engine air is unknown and, consequently, the end loss cannot be calculated in advance. Assume that the end loss is 10 pounds per square foot. The maximum allowable Δp_e in the tubes is then 60.7 pounds per square foot.

From figure 5, estimate that $\zeta = 0.45$ for $\xi = 0.578$. Then, with $\zeta = 0.45$, the limit on $\Delta p_e'$ is as given in table I. In order to obtain a small volume, choose the maximum $\Delta p_e'$; that is, choose $\Delta p_e' = 0.69$. In order to obtain the lowest power expenditure for this pressure drop, choose $\Delta p_c' = 0.4$, which is the value of $\Delta p_c'$ for tubular intercoolers for minimum power, as pointed out previously in the Discussion of Charts. The intersection of these two $\Delta p'$ curves gives the point on the selection chart (fig. 3) that represents the intercooler. The values of the other generalized variables at this point are as listed in table I.

It is well to apply the following checks at this stage in the procedure. If the values of the variables have been correctly read from the chart, the following equations will be satisfied:

$$P' = \Delta p_c' + v'$$

$$v' = L_e' L_c' L_n'$$

In order to make M_c/M_e reasonably large, choose the maximum L_n. Then, from the relation defining L_n'

$$L_n' = \frac{2.13}{M_c/M_e} = 1.14$$

and

$$M_c/M_e = 1.87$$

For this value of M_c/M_e, $\zeta = 0.51$ in figure 5. With these values of M_c/M_e and ζ, the values of the pressure drops, the dimensions, and so forth, of the intercooler, calculated from form 3, are as given in table I. More exact values of these variables are found by relocating on the chart the point that represents the intercooler, using a more exact estimate for the value of ζ. This procedure gives the results shown in the second column under Example I in table I. The proper values for all of the intercooler variables have now been found.

The end loss (pressure loss at the entrance and at the exit of the intercooler) for the cooling air has been taken care of in the constants that have been used and is included in the value found for Δp_c. The entrance loss for the engine air is negligible, inasmuch as the ends of the tubes are flared. The exit loss for the engine air is given in pounds per square foot by the equation

$$(1 - f_e)^2 \frac{\rho_e V_e^2}{2} = 0.068\left(\frac{T_{e_{out}} + 460}{p_{e_{out}}}\right)\left(\frac{M_e}{L_c L_n}\right)^2$$

For the design conditions given above, the exit loss is $22/(L_c L_n)^2$ pounds per square foot. The value of P_e is given in horsepower by the equation

$$P_e = 0.00137 \left(\frac{T_e + 460}{\overline{p}_e}\right) M_e \Delta p_e$$

For the given design conditions, the value of P_e in horsepower may be written

$$P_e = 0.116 \, \Delta p_e$$

Example II.- In order to illustrate the fact that the use of a smaller Δp_e makes a larger volume necessary, an intercooler will be selected for the same conditions as in example I, with the exception that Δp_e is only one-half of the maximum value allowable. Assume that Δp_e, including end loss, is 35 pounds per square foot and that Δp_e, excluding end loss, is 30 pounds per square foot.

Assume $\zeta = 0.48$. Under Example II in table I are listed the limits on the pressure drops, on L_n, and on $\Delta p_e{}'$. Choosing $\Delta p_e{}' = 0.36$ and $\Delta p_c{}' = 0.4$ fixes the point on figure 3 that represents the intercooler. The values of the other generalized variables at this point are as listed. Choosing $L_n = 3$ feet gives $M_c/M_e = 1.45$, and figure 5 gives $\zeta = 0.46$. The values of the other variables are as listed. This case illustrates the fact that a smaller Δp_e requires the use of a larger volume. In example I, $\Delta p_e = 67.5$ pounds per square foot and $v = 5.8$ cubic feet. In example II, $\Delta p_e = 34$ pounds per square foot and $v = 7.2$ cubic feet, an increase of 24 percent in volume.

Example III.- Example III is given to illustrate the effects of the use of a larger Δp_c and of too small a ratio M_c/M_e. Three cases are calculated, for each of which Δp_c is chosen in advance to be 23.6 pounds per square foot. The value of Δp_e is assumed to be 60.7 pounds per square foot plus an end loss of 10 pounds per square foot.

(a) Choose $\Delta p_c{}' = 0.4$.

Because $\Delta p_c{}' = 0.0605 \, \zeta \dfrac{M_c}{M_e} \Delta p_c$ and because $\Delta p_c{}'$ has the same value while Δp_c is about three times as large as in example I, it is clear that M_c/M_e and ζ will probably be so small that the volume and the power expenditure will be excessive. Substitution in the preceding equation gives $\zeta(M_c/M_e) = 0.28$. Figure 5 then gives $M_c/M_e = 0.91$ and $\zeta = 0.31$. Then $\Delta p_e' = 0.47$. When $\Delta p_e'$ and $\Delta p_c'$ are known, the point on the selection chart is fixed. The values of the other generalized variables are as listed in table I, as are the values of the unprimed variables.

It is seen that, because M_c/M_e is to the left of the knee, ζ is small and that, on account of the small temperature difference, the necessary surface and volume are excessively large. The power expenditure is correspondingly large.

(b) In order to obtain larger values for M_c/M_e and ζ, choose a larger $\Delta p_c'$. In order to obtain $\zeta \cong 0.5$, make both ζ and M_c/M_e about twice as large as in the preceding case. Then, $\Delta p_c'$ will be about four times as large as in the preceding case. Choose $\Delta p_c' = 1.6$. From the equation relating Δp_c and $\Delta p_c'$, $\zeta(M_c/M_e) = 1.12$; and, from figure 5, $M_c/M_e = 2.10$ and $\zeta = 0.53$. The values of the generalized variables and of the corresponding unprimed variables are given in table I. Both the volume and the power are considerably less than in example III(a) because of the larger value of M_c/M_e. The volume is also less than in example I because of the larger value of $\Delta p_c'$.

(c) One more intercooler will be selected under the conditions of example III in order to show that, as M_c/M_e is increased still further, the decrease in volume becomes negligible and L_n becomes excessive. Choose $\Delta p_c' = 2.6$. Then $\zeta(M_c/M_e) = 1.82$, and figure 5 gives $M_c/M_e = 3.15$ and $\zeta = 0.58$. The values of the other variables are as listed in table I. It is seen that there is only a 16-percent decrease in volume and a 35-percent increase in L_n over the values of example III(b). In fact, L_n must be greater than the 3 feet that had been set as a limit.

Example IV.- The purpose of example IV is to show how the charts can be used to ascertain the pressure drops and the mass flow of cooling air necessary to obtain a given rate of heat transfer in an intercooler of given dimensions. Assume the same design conditions that were used in the previous examples. Assume that the intercooler has the following dimensions:

L_e, feet 2

L_c, foot 1

L_n, feet 3

v, cubic feet 6

Assume that $\zeta = 0.51$. Then $L_e' = 1.30$ and $v' = 3.24$. The intersection of these two curves gives the point that represents the intercooler. The values of the other generalized variables at this point are as given in table I. From the known values of L_c and L_c' and from the equation

$$L_c' = 2.61 \frac{M_c}{M_e} \zeta L_c$$

$\zeta(M_c/M_e) = 0.97$ and, from figure 5, $M_c/M_e = 1.90$ and $\zeta = 0.51$. The values of the necessary pressure drops and the power expenditure can now be calculated and are as given in table I.

Example V.- Example V illustrates the selection of a Harrison copper intercooler. Assume that the intercooler is to be chosen for the same design conditions that were used in selecting the Airesearch intercoolers in the preceding examples. The values of the constants are obtained by filling in forms 4 and 3 (in that order).

Assume the limits on the pressure drops and on the no-flow dimension as given in table I. Assume $\zeta = 0.48$. Then the limit on $\Delta p_e'$ is as given in table I. Choose $\Delta p_e' = 2.72$ and $\Delta p_c' = 0.6$. The values of the other generalized variables are then fixed and are as given in table I. Choose $L_n = 3$ feet. From the relation

$$L_n' = \frac{1.02}{\frac{M_c}{M_e}} = 0.65$$

$$M_c/M_e = 1.57$$

and from figure 5, $\zeta = 0.47$. The values of the pressure drops, dimensions, and power expenditure can then be calculated and are as given in table I.

The values of the constants used in defining the generalized variables for the Harrison intercooler are such that end loss is included in the values obtained from the chart for Δp_c and Δp_e.

CONCLUDING REMARKS

The generalized selection charts presented for Harrison and tubular intercoolers facilitate the rigorous selection of intercoolers for any set of conditions. The charts also show the effects of varying the different intercooler characteristics. The examples given illustrate the practical use of the charts.

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APPENDIX

CONSTRUCTION OF THE CHARTS

In reference 5 an analysis was made of heat exchangers installed in aircraft, and generalized equations were developed that describe the performance of such heat exchangers. In order that these equations may be used for the construction of selection charts for specific types of heat exchangers (in this instance tubular and Harrison type cross-flow intercoolers), numerical values must be assigned to the exponents in the pressure-drop and the heat-transfer equations used in the development of the generalized equations. Then, in order that the charts may be used for the selection of intercoolers, numerical values must be assigned to the coefficients in these pressure-drop and heat-transfer equations. For the flow across tubes, the pressure-drop equation and the heat-transfer equation are, respectively:

$$\frac{\Delta p_a m_p}{4 \frac{\rho_a V_a^2}{2} L_a} = c_3 \left(\frac{\mu_a}{\rho_a V_a D_a}\right)^x \qquad (1)$$

and

$$\frac{h_a D_a}{k_a} = c_2 \left(\frac{\beta_a V_a \rho_a}{\mu_a}\right)^u \tag{2}$$

For the flow through tubes these equations are, respectively:

$$\frac{\Delta p_b D_b}{4 \frac{\rho_b V_b^2}{2} L_b} = c_2 \left(\frac{\mu_b}{\rho_b V_b D_b}\right)^y \tag{3}$$

and

$$\frac{h_b D_b}{k_b} = c_4 \left(\frac{\rho_b V_b D_b}{\mu_b}\right)^v \tag{4}$$

The best values for the exponents and the coefficients in equations (1) to (4) for two intercoolers are given in the following table:

Intercooler	Exponent	Value of exponent	Coefficient	Value of coefficient
Airesearch,	u	0.6	c_1	0.125
tubular	v	.8	c_2	.049
	x	.13	c_3	.269
	y	.2	c_4	.019
Harrison,	u	0.8	c_1	0.11
copper	v		c_2	
	x	.2	c_3	.0247
	y		c_4	

The values for the Airesearch intercooler were found from data given in reference 6, in which the data published in references 7 and 8 are correlated. The values for the Harrison intercooler were obtained from the data published in reference 9.

The selection charts (figs. 3 and 4) were constructed from the following generalized equations in which the exponents given in the preceding table have been used. The subscripts c for cooling air and e for engine air have been substituted, respectively, for the subscripts a and b that appear in similar equations in reference 5, and v' has been substituted for $L_e'L_c'L_n'$. The equations for tubular intercoolers are:

$$P' = v'\left\{1 + \frac{1}{\left[v' - \left(\frac{v'}{\Delta p_e'}\right)^{0.286}\right]^{4.78}}\right\} \tag{5}$$

$$v' = P' - \Delta p_c' \tag{6}$$

$$P' = v'\left\{1 + \frac{1}{\left[v' - \left(\frac{v'}{L_e'}\right)^{0.8}\right]^{4.78}}\right\} \tag{7}$$

$$P' = v'\left[1 + \left(\frac{L_c'}{v'}\right)^{2.87}\right] \tag{8}$$

$$L_n'v' = A_e'\left[v' - (A_e')^{0.8}\right]^{5/3} \tag{9}$$

$$P' = v'\left[1 + \left(\frac{A_e'}{L_n'v'}\right)^{2.87}\right] \tag{10}$$

The equations for Harrison intercoolers are:

$$P' = v'\left\{1 + \frac{1}{\left[v' - \left(\frac{v'}{\Delta p_e'}\right)^{1/3.5}\right]^{3.5}}\right\} \tag{11}$$

$$v' = P' - \Delta p_e' \tag{12}$$

$$P' = v'\left\{1 + \frac{1}{\left[v' - \left(\frac{v'}{L_e'}\right)^{0.8}\right]^{3.5}}\right\} \tag{13}$$

$$P' = v'\left[1 + \left(\frac{L_c'}{v'}\right)^{2.8}\right] \tag{14}$$

$$L_n'v' = A_e'\left[v' - (A_e')^{0.8}\right]^{1.25} \tag{15}$$

$$P' = v'\left[1 + \left(\frac{A_e'}{L_n'v'}\right)^{2.8}\right] \tag{16}$$

For tubular intercoolers, curves of constant $\Delta p_e'$ and v' (fig. 3) were drawn from equations (5) and (6), and curves of constant L_e', L_c', and L_n' (fig. 3) were drawn from equations (6) to (10). For Harrison intercoolers, curves of constant $\Delta p_e'$ and v' (fig. 4) were drawn from equations (11) and (12), and curves of constant L_e', L_c', and L_n' (fig. 4) were drawn from equations (12) to (16). The chart for each type of intercooler has been separated into two parts for the sake of clarity.

The definitions of the generalized variables contain the constants α_1, α_2, α_3, and α_4. (In reference 5 these constants are designated ϕ_1, ϕ_a, ϕ_b, θ_b, respectively.) These constants are functions of the general type of intercooler, of the internal dimensions of the intercooler, and of the average physical characteristics of the fluids, $\overline{\mu}$, $\overline{\rho}$, and $\overline{K}$. These characteristics are, in turn, functions only of the average temperatures and pressures of the fluids. A large reduction in the amount of numerical calculation necessary to determine the values of these constants for an intercooler of a given type and internal dimensions and for a given set of design conditions is effected by plotting the constants as functions of the average temperatures and pressures of the fluids. A plot of any one of the α's could be used only for an intercooler of a given type and of given internal dimensions. In order to obtain plots that can be used for intercoolers of any internal dimensions and of any type, the constants β_1, β_2, β_3, and β_4 are plotted. (See figs. 6, 7, and 8.) The α's can be obtained from the values of the corresponding β's by multiplying by the proper proportionality factors. (See forms 2 and 4.) In order that a single plot of β_1 can be used for both tubular and Harrison intercoolers, the exponents were averaged. The resulting inaccuracy is negligibly small. No adjustment of exponents was necessary in plotting β_2, β_3, and β_4.

Figure 5, which shows the variation of $1/\zeta$ with ξ and M_c/M_e, was drawn from results published in reference 10.

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TABLE I

VALUES OF INTERCOOLER VARIABLES USED IN EXAMPLES

	EXAMPLE								Units
	I		II	III			IV	V	
	First trial	Second trial		a	b	c			
Limit on Δp_e	70.7	70.7	35.0	70.7	70.7	70.7	----	70.7	lb/sq ft
Limit on Δp_c	23.6	23.6	23.6	23.6	23.6	23.6	----	23.6	lb/sq ft
Limit on L_n	3	3	3	3	3	3	----	3	ft
Estimated ζ	.45	.50	.48	----	----	----	0.51	.48	
Limit on $\Delta p_e'$	.69	.76	.36	----	----	----	----	2.72	
$\Delta p_e'$	0.69	0.76	0.36	0.47	0.81	0.89	0.25	2.72	
$\Delta p_c'$	.4	.4	.4	.4	1.60	2.60	1.60	.6	
P'	3.48	3.42	3.90	3.70	4.06	4.87	4.84	3.06	
v'	3.08	3.02	3.50	3.30	2.46	2.27	3.24	2.46	
L_c'	1.51	1.48	1.65	1.60	2.12	2.38	2.52	1.49	
L_e'	1.79	1.82	1.54	1.63	1.66	1.64	1.30	2.54	
L_n'	1.14	1.12	1.38	1.27	.70	.58	.99	.65	
M_c/M_e	1.87	1.68	1.45	.91	2.10	3.15	1.90	1.57	
ζ	.51	.49	.46	.31	.53	.58	.51	.47	
Δp_e less end loss	53.8	62.0	31.1	60.7	60.7	60.7	19.4	----	lb/sq ft
End loss	5.1	5.5	2.9	3.7	6.8	8.1	2.4	----	lb/sq ft
Total Δp_e	58.9	67.5	34.0	64.4	67.5	68.8	21.8	70.7	lb/sq ft
Δp_c	6.9	8.0	10.1	23.6	23.6	23.6	27.3	22.3	lb/sq ft
L_n	3.4	2.9	2.9	1.11	2.45	3.30	3.0	3.0	ft
L_c	.61	.69	.95	2.20	.73	.50	1.0	.60	ft
L_e	2.77	2.93	2.64	4.14	2.47	2.22	2.0	1.54	ft
v	5.75	5.80	7.2	10.0	4.38	3.70	6.0	2.74	cu ft
$P_W + P_c$	28.4	29.6	36.1	50.6	32.6	35.7	40.4	46.0	hp
P_e	6.8	7.8	3.9	7.5	7.8	8.0	2.5	8.2	hp
P_t	35.2	37.4	40.0	58.1	40.4	43.7	42.9	54.2	hp

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Selection Form 1

(For all intercoolers)

Quantity		Symbol	Value	Unit
Engine power			2000	hp
Engine-air weight flow		M_e	4.21	lb/sec
Engine-air inlet temperature			230	°F
Engine-air outlet temperature		$T_{e_{out}}$	90	°F
Engine-air inlet pressure			31.25	in. Hg
Engine-air outlet pres. (Estimated)		$p_{e_{out}}$	30.25	in. Hg
Engine-air mean temperature		$\overline{T}_e$	160	°F
Engine-air mean pressure		$\overline{p}_e$	30.75	in. Hg
Airplane velocity		V_o	660	fps
Altitude			30,000	ft
Pressure at altitude			8.88	in. Hg
Impact pressure			2.98	in. Hg
Cooling-air pressure available			11.86	in. Hg
Cooling-air duct loss	Estimated		.5	in. Hg
Cooling-air inlet pressure	Estimated		11.36	in. Hg
Cooling-air outlet pressure	Estimated		11.16	in. Hg
Cooling-air mean pressure	Estimated	$\overline{p}_c$	11.26	in. Hg
Temperature at altitude			-48	°F
Adiabatic temperature rise			36	°F
Cooling-air inlet temperature			-12	°F
Cooling-air weight flow	Estimated	M_c	1.4 M_e	lb/sec
Cooling-air outlet temperature	Estimated		88	°F
Cooling-air mean temperature	Estimated	$\overline{T}_c$	38	°F
$\frac{\text{Engine-air temperature drop}}{\text{Initial temperature difference}}$		ξ	.578	
Weight factor		ϵ	1.5	
Drag-lift ratio		C_D/C_L	1/8	
Duct efficiency (cooling air)		η_c	1	

Selection Form 2

(For Airesearch tubular-type intercoolers (fig. 2)).

	Constant	Value
From figure 6 at $\overline{T}_c$ and $\overline{p}_c$	β_1	1.05
$500\ \beta_1/\eta_c$	α_1	525
From figure 7 at $\overline{T}_c$	β_2	1.941
$597\ (\beta_2)^2$	α_2	2250
From figure 7 at $\overline{T}_e$	β_3	1.873
$2385\ \beta_3$	α_3	4470
From figure 8 at $\overline{T}_e$ and $\overline{p}_e$	β_4	2.62
$2\ \beta_4$	α_4	5.24
$20\ \epsilon\ C_D/C_L\ V_o$	α_5	2480
$(\alpha_5/\alpha_1)^{0.21}$	α_6	1.38
$\dfrac{4210\alpha_6}{\alpha_2\alpha_5 M_e\ \zeta}$	K_1	4.28×10^{-4}
$\left(\dfrac{\alpha_3\alpha_6}{\alpha_2}\right)^{1.25}$	K_2	3.52
$K_2^{2.8}$	K_3	33.9
$\dfrac{\alpha_6^{\ 1.66}}{\alpha_5}$	K_4	6.9×10^{-4}

Selection Form 4

(For Harrison copper intercoolers (fig. 1))

	Constant	Value
From figure 6 at $\overline{T}_c$ and $\overline{p}_c$	β_1	1.05
$600\ \beta_1/\eta_c$	α_1	630
From figure 7 at $\overline{T}_c$	β_2	1.941
$1394\ \beta_2$	α_2	2710
From figure 7 at $\overline{T}_e$	β_3	1.873
$1394\ \beta_3$	α_3	2610
From figure 8 at $\overline{T}_e$ and $\overline{p}_e$	β_4	2.62
$3.77\ \beta_4$	α_4	9.88
$60\ \epsilon\ V_o\ C_D/C_L$	α_5	7420
$(\alpha_5/\alpha_1)^{\frac{1}{3.5}}$	α_6	2.02
$\dfrac{6250\alpha_6}{\alpha_2\alpha_5 M_e\ \zeta}$	K_1	2.58×10^{-4}
$\left(\dfrac{\alpha_3\alpha_6}{\alpha_2}\right)^{1.25}$	K_2	2.29
$K_2^{2.8}$	K_3	10.2
$\dfrac{\alpha_6^{\ 1.25}}{\alpha_5}$	K_4	3.25×10^{-4}

Selection Form 3

(For all tubular-type and all Harrison type intercoolers)

[Values for Harrison copper intercoolers]

Constant	Value	Variable	Generalized variable (a)
$\frac{\alpha_5 K_1 M_e}{\alpha_4 K_3}$	0.080	$\zeta \Delta p_e$	$\Delta p_e'$
$\frac{K_1(\overline{T}_c + 460)M_e}{1.32\eta_c \overline{p}_c}$	.0364	$\frac{M_c}{M_e} \zeta \Delta p_c$	$\Delta p_c'$
$\frac{\alpha_5 K_1 M_e}{K_2}$	3.52	ζL_e	L_e'
$\frac{K_1 M_e}{K_4}$	3.34	$\frac{M_c}{M_e} \zeta L_c$	L_c'
$\frac{K_2 K_4}{K_1 M_e^2}$	.163	$\frac{L_n}{\frac{M_c}{M_e} \zeta}$	L_n'
$\alpha_5 K_1$	1.91	ζv	v'
$550\ K_1$	.142	$\zeta (P_w + P_c)$	P'

[a]Generalized variable = Constant × Variable.

Selection Form 3

(For all tubular-type and all Harrison type intercoolers)

[Values for Airesearch tubular intercoolers]

Constant	Value	Variable	Generalized variable (a)
$\frac{\alpha_5 K_1 M_e}{\alpha_4 K_3}$	0.0252	$\zeta \Delta p_e$	$\Delta p_e'$
$\frac{K_1(\overline{T}_c + 460)M_e}{1.32\eta_c \overline{p}_c}$	.0605	$\frac{M_c}{M_e} \zeta \Delta p_c$	$\Delta p_c'$
$\frac{\alpha_5 K_1 M_e}{K_2}$	1.27	ζL_e	L_e'
$\frac{K_1 M_e}{K_4}$	2.61	$\frac{M_c}{M_e} \zeta L_c$	L_c'
$\frac{K_2 K_4}{K_1 M_e^2}$	.320	$\frac{L_n}{\frac{M_c}{M_e} \zeta}$	L_n'
$\alpha_5 K_1$	1.06	ζv	v'
$550\ K_1$	.24	$\zeta (P_w + P_c)$	P'

[a]Generalized variable = Constant × Variable.

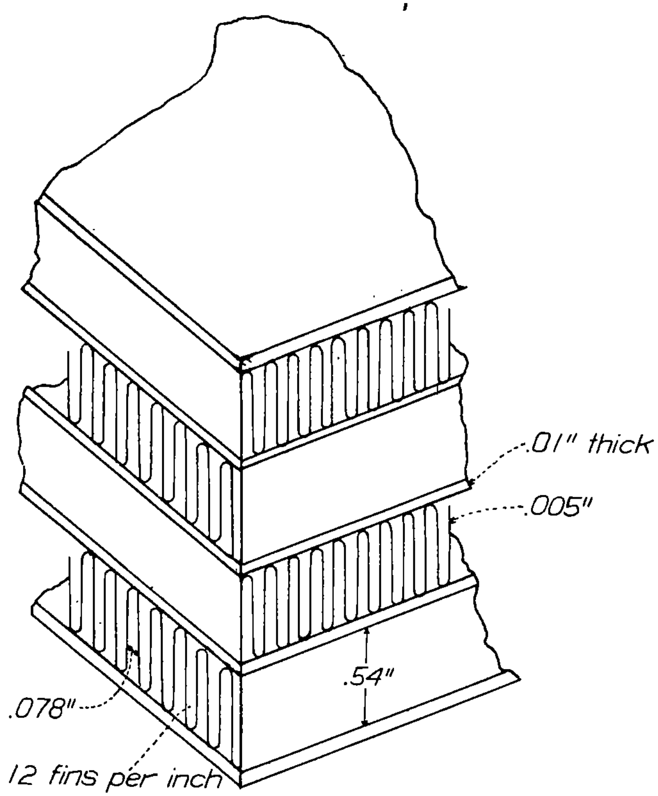

Figure 1.- Internal geometry and dimensions of Harrison copper intercooler.

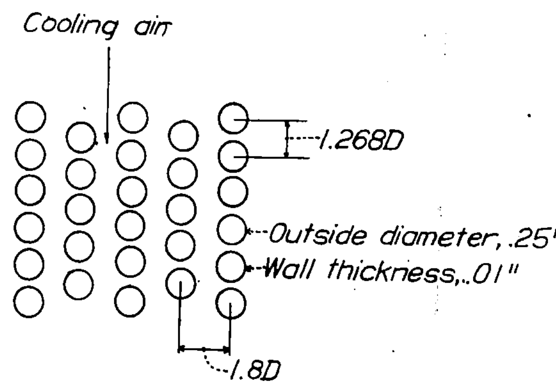

Figure 2.- Internal geometry and dimensions of Airesearch tubular aluminum intercooler.

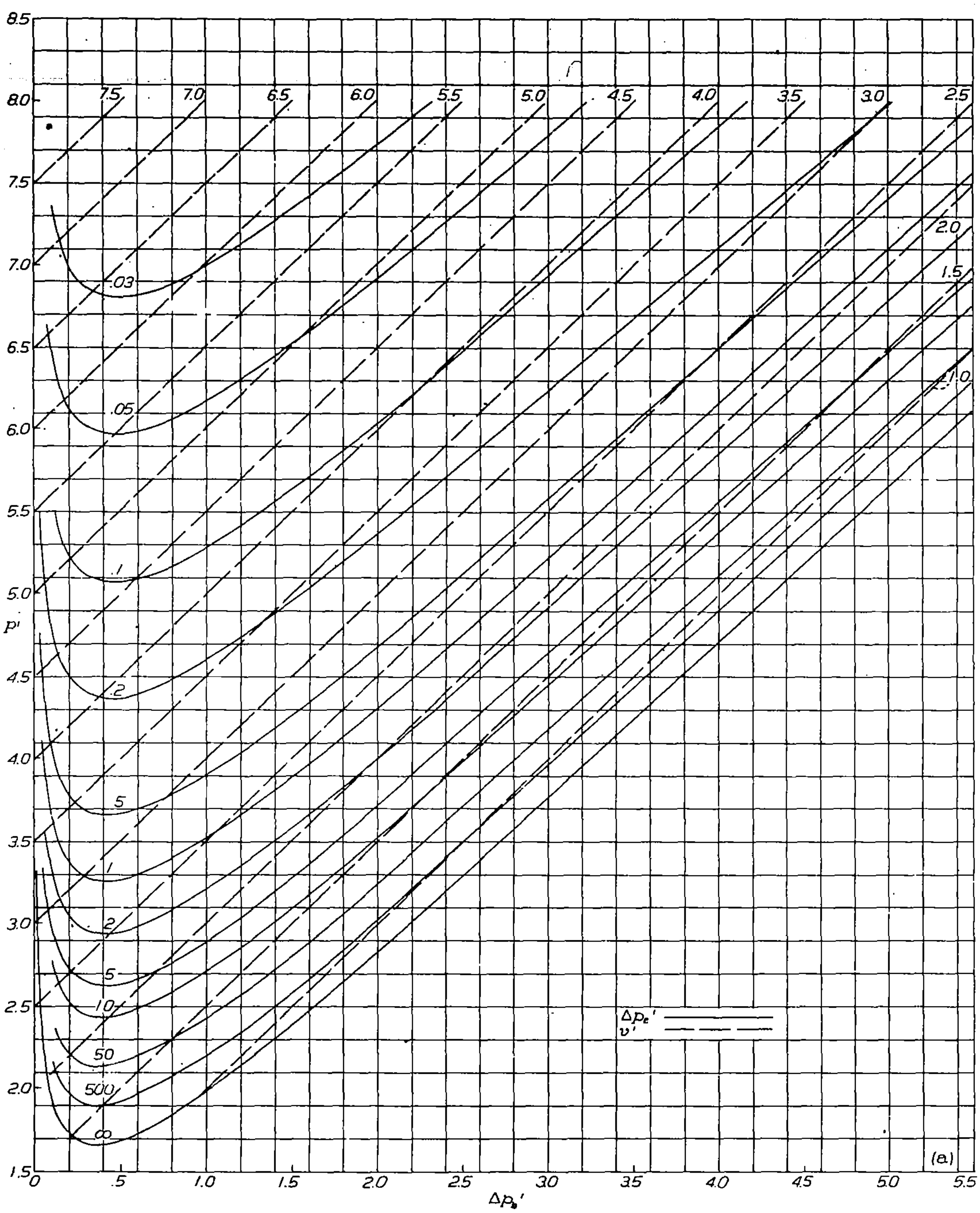

Figure 3.- Generalized selection chart for tubular intercoolers.

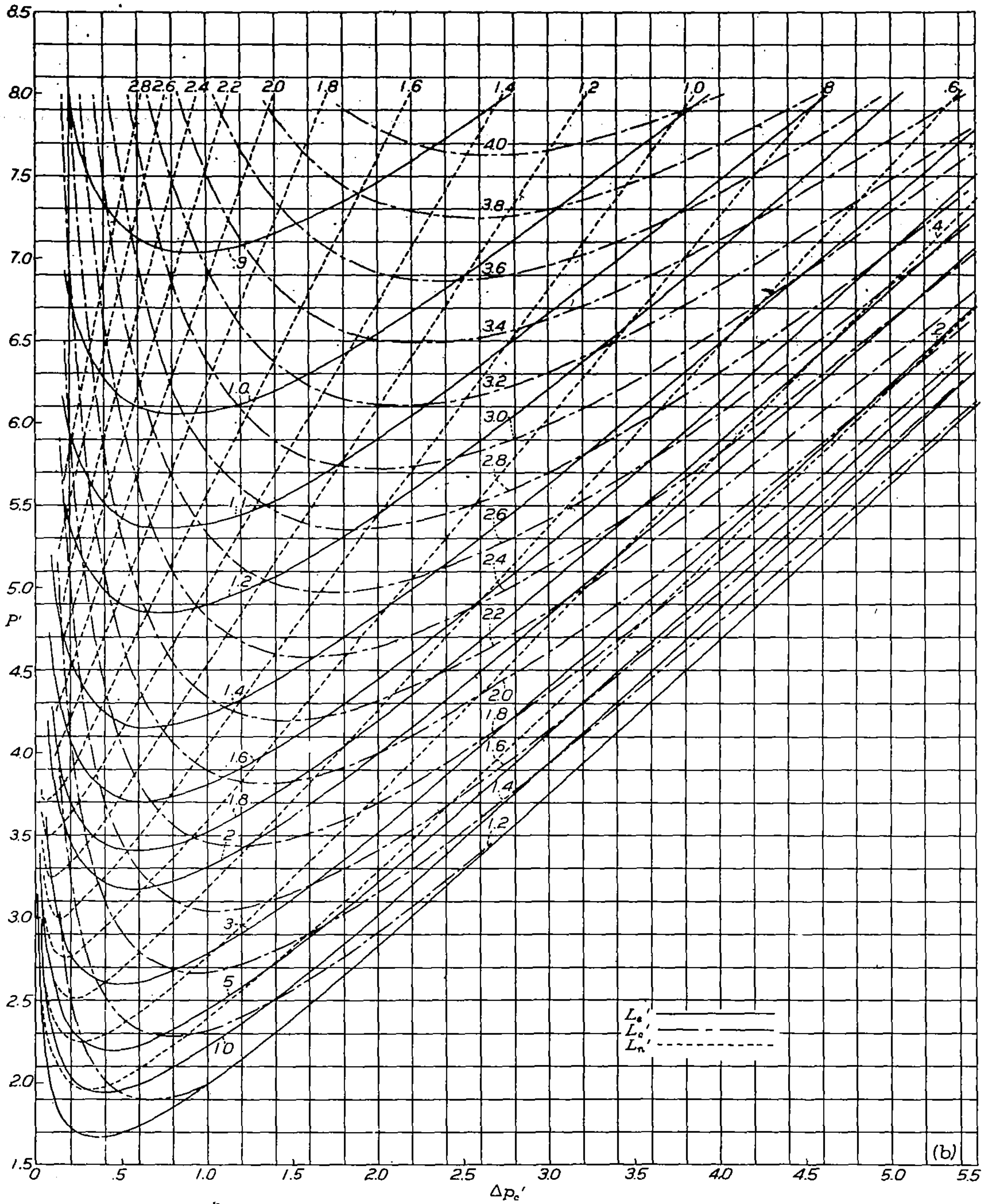

Figure 3.- Concluded.

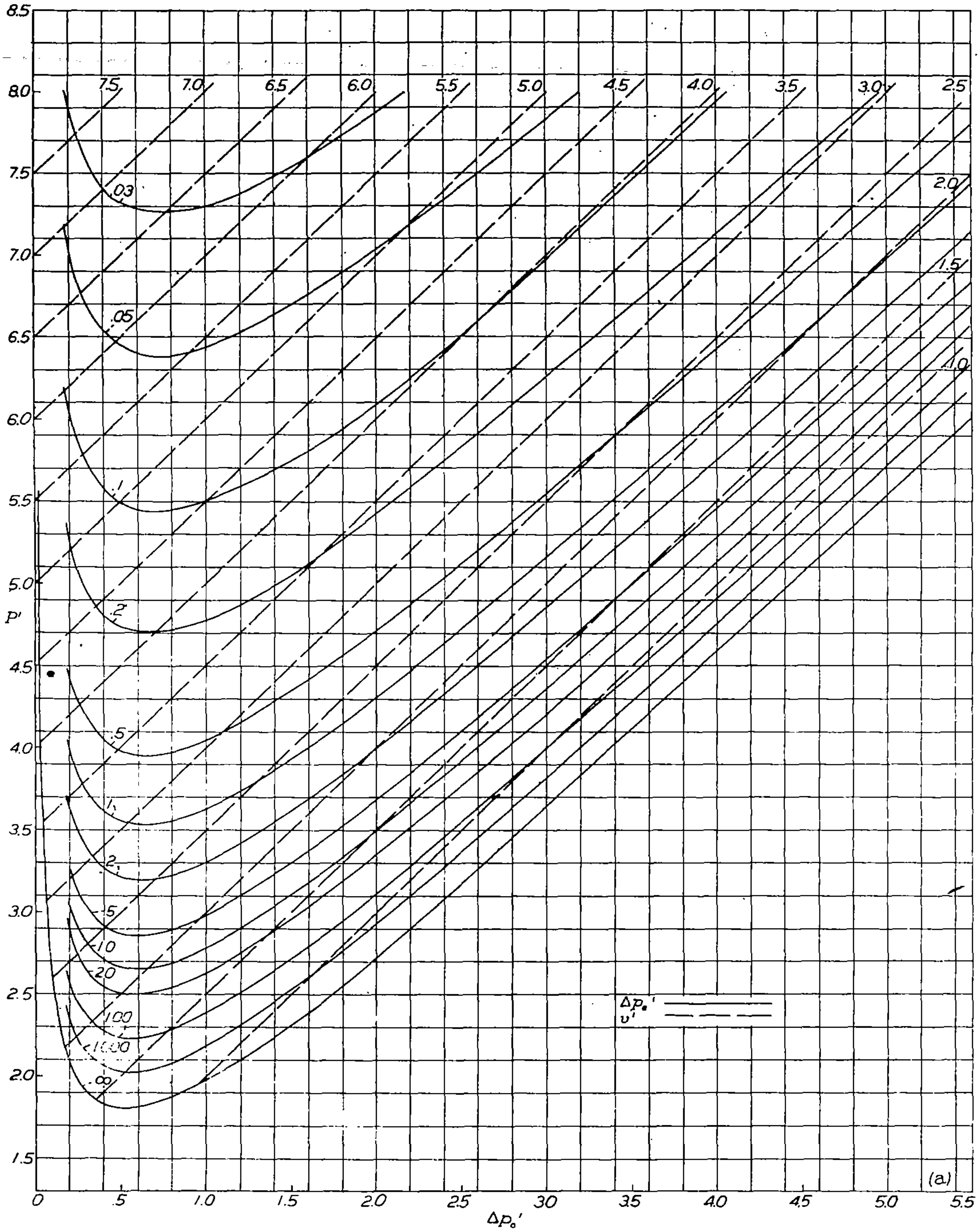

Figure 4.- Generalized selection chart for Harrison intercoolers.

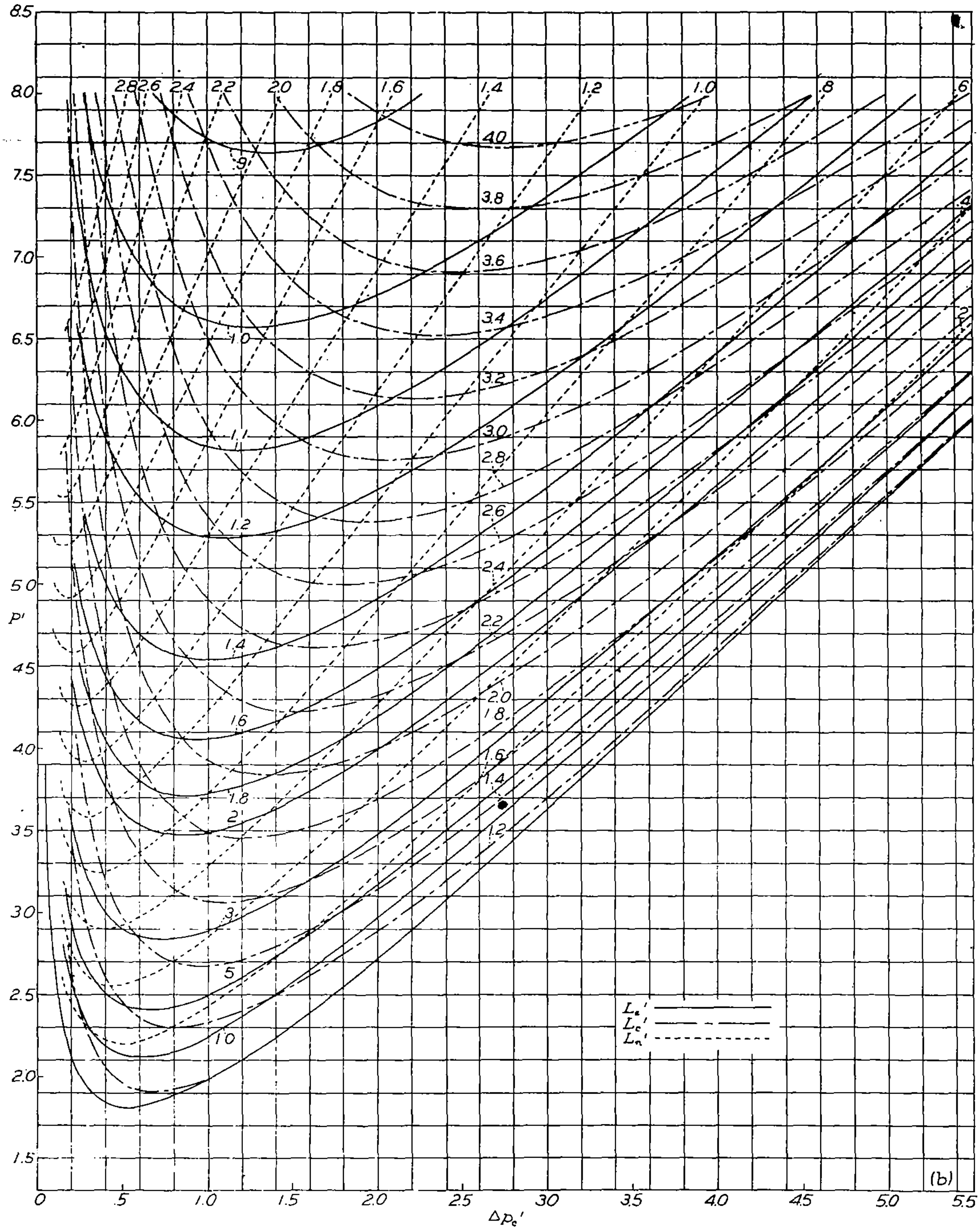

Figure 4.- Concluded.

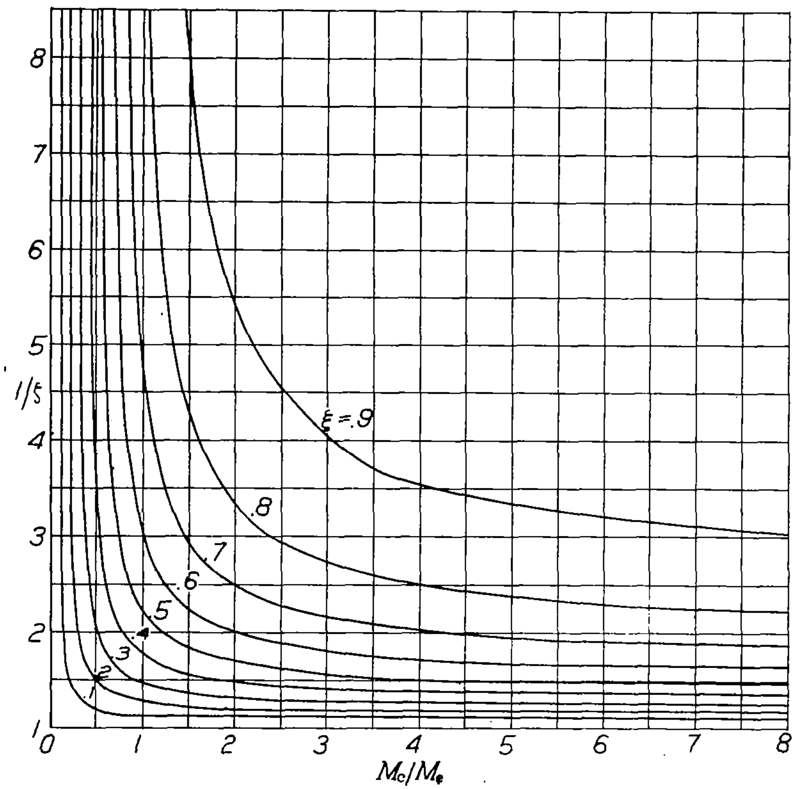

Figure 5.- Variation of $1/\zeta$ with M_c/M_e. Data from reference 10.

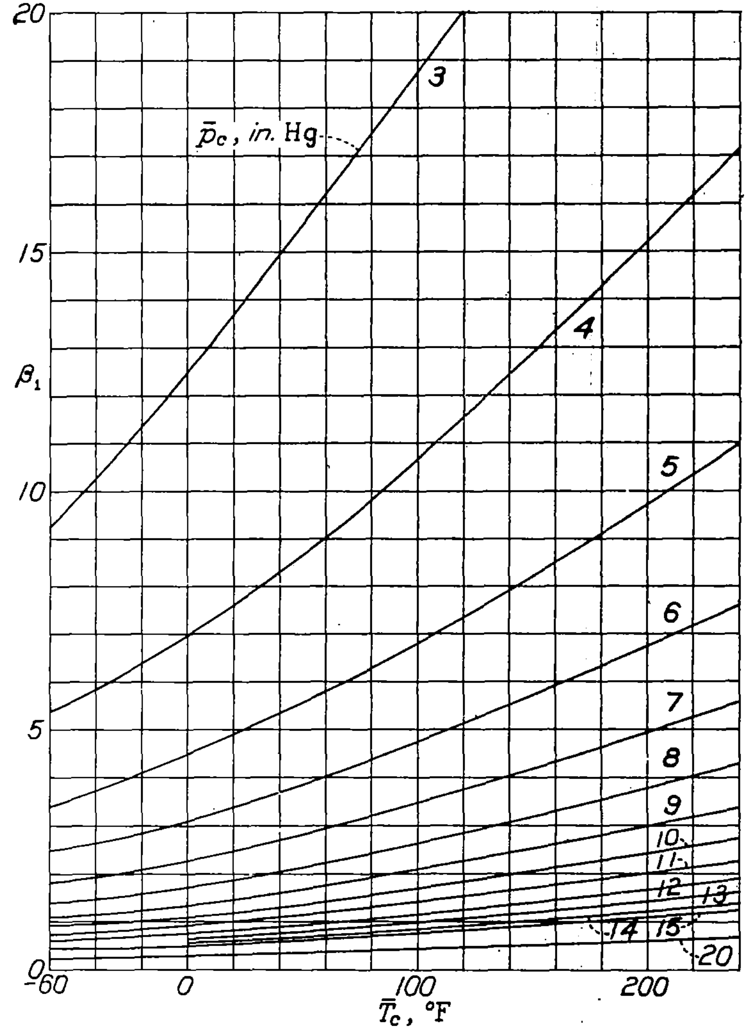

Figure 6.- Variation of β_1 with mean temperature and pressure for Harrison and tubular intercoolers.

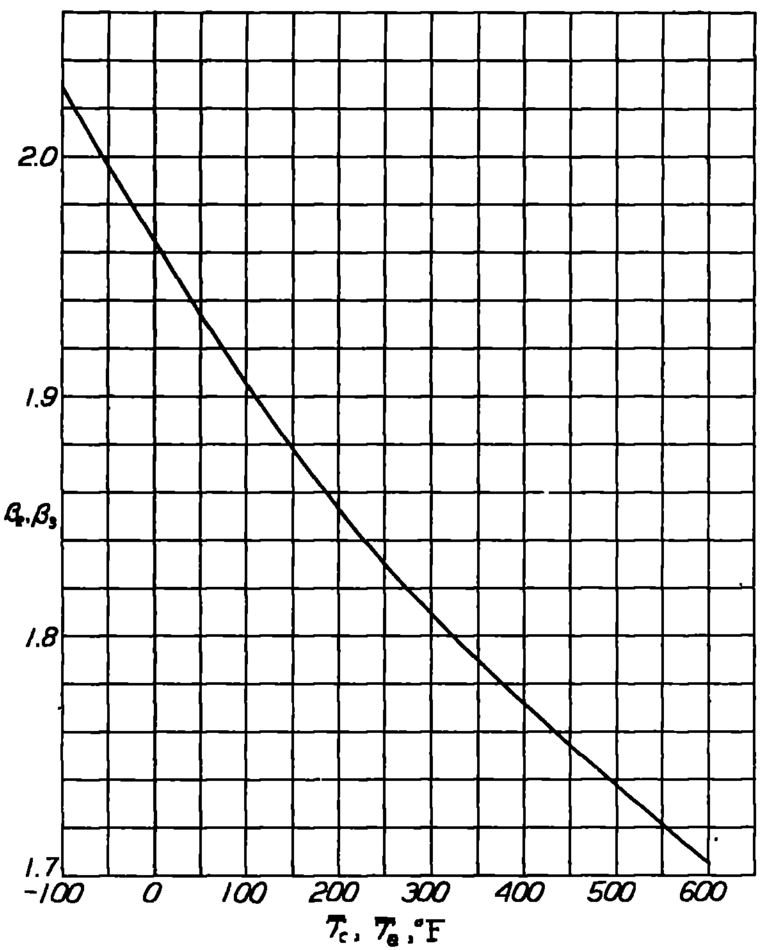

Figure 7.- Variation of β_2 and β_3 with mean temperature for Harrison and tubular intercoolers.

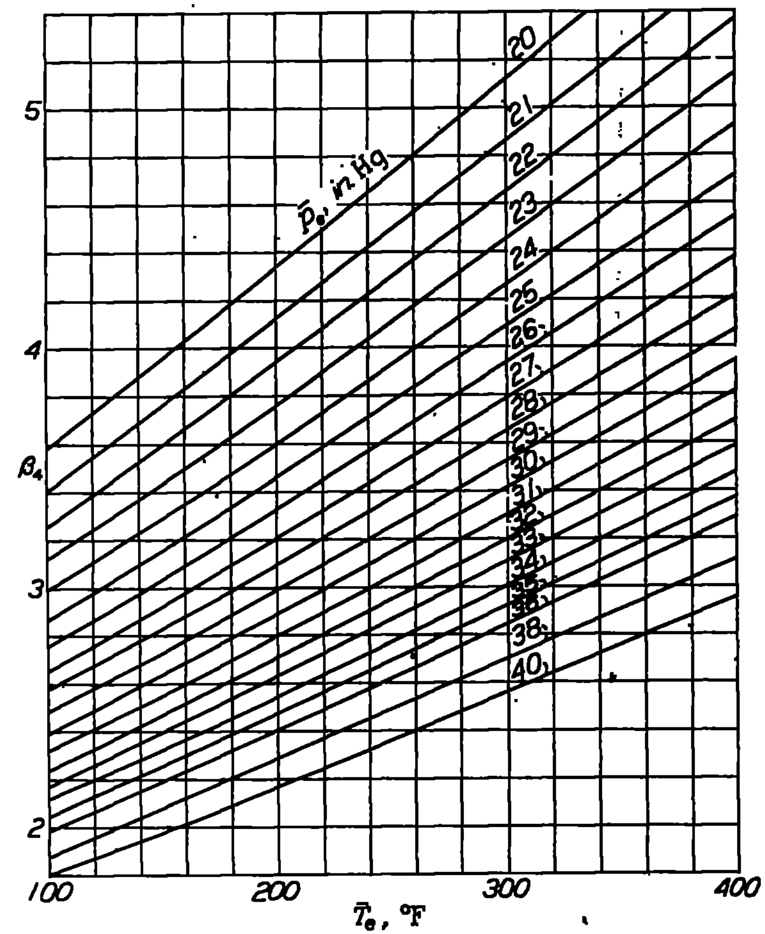

Figure 8.- Variation of β_4 with mean temperature and pressure for Harrison and tubular intercoolers.